Development of a Rooftop Collaborative Experimental Space through Experiential Learning Projects

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Abstract

The Solar, Water, Energy, and Thermal Laboratory (SWEAT Lab) is a rooftop experimental space at the University of Texas at Austin built by graduate and undergraduate students in the Cockrell School of Engineering. The project was funded by the Texas State Energy Conservation Office and the University's Green Fee Grant, a competitive grant program funded by UT Austin tuition fees to support sustainability-related projects and initiatives on campus. The SWEAT Lab is an on-going experiential learning facility that enables engineering education by deploying energy and water-related projects. To date, the lab contains a full weather station tracking weather data, a rainwater harvesting system and rooftop garden.

This project presented many opportunities for students to learn first hand about unique engineering challenges. The lab is located on the roof of the 10 story Engineering Teaching Center (ETC) building, so students had to design and build systems with constraints such as weight limitations and wind resistance. Students also gained experience working with building facilities and management for structural additions, power, and internet connection for instruments.

With the Bird's eye view of UT Austin campus, this unique laboratory offers a new perspective and dimension to applied student research projects at UT Austin.

1. Introduction

Energy and water research are and have been important topics for research at the University of Texas. Students in the Webber Energy Group at UT (led by professor Michael Webber) built their own rooftop lab to learn by doing and to collect the data they could not find elsewhere. The lab has served as a free-form 'maker space' for solar and water researchers, and there is on-going work to expand this space to include food and food waste systems as well. This paper provides the motivation of the lab, an accounting of the equipment and systems that are included, and a description of the student research and other projects associated with the lab. This paper concludes with lessons learned so far and plans for the future.

2. Motivation

The genesis of the SWEAT Lab started in 2012 when graduate student Joshua Rhodes determined there was a lack of publicly available solar insolation data co-located with a meteorological station in Austin, Texas that could be used for teaching and research purposes.

After an exhaustive search for solar radiation data from local solar panel manufacturers, solar installers, solar inverter manufacturers, labs at UT-Austin, Austin Community College's solar installation training program, the National Renewable Energy Lab, and Austin Energy's 30MW solar farm (just outside of town), the only source of local radiation data was found to be a local elementary school that, as part of the State Energy Conservation Office's Solar for Schools project, had been collecting data for several years. However, their pyranometer had become inoperable in 2010 and, for lack of funds, had not been repaired.

Supported by funding from the Department of Energy and the Doris Duke Charitable Foundation, Pecan Street Inc., an Austin-based public-private partnership that created a smart grid demonstration project provided funding for architectural engineering PhD student Joshua Rhodes (under advisor Professor Michael Webber) to refurbish and manage the solar radiation monitoring equipment on the roof of ETC. As part of this process, equipment was added and the scope of the lab's capabilities was defined with its new name: Solar Water Energy And Thermal Lab (SWEAT Lab).

3. SWEAT Lab Equipment and System Descriptions

3.1 Solar and Meteorological Instruments

Creating the SWEAT Lab started with repairing and replacing the original instruments, then expanding and modernizing the data collection capabilities. In addition to refurbishing (and then replacing) the solar radiation equipment, Joshua added a full meteorological station and associated data collection systems for air temperature, relative humidity, wind speed and direction, and precipitation. All data are displayed in real time on the research group's website and is made available to students and the public for research, analysis, and student projects [1]. An archive of the data since Summer 2012 is maintained by the Webber Energy Group and the Texas Advanced Computing Center (TACC) [2].

Table 1 below lists all instruments incorporated into the SWEAT Lab that are currently collecting weather data for the downtown Austin area:

Table 1: List of instruments currently in operation in SWEAT Lab

Solar Data Collection Instruments:	**Weather Data Equipment:**
Kipp & Zonen Automatic Solar Tracker Model SMT	Met One 010C Wind Speed Sensor (See Figure 2a)
Eppley Lab Equipment:	Met One 020C Wind Direction Sensor (See Figure 2b)
Direct Pyrheliometer (See Figure 1a)	Vaisala HMP60 Temperature and Humidity Sensor (See Figure 2c)
Global Horizontal Pyranometer (See Figure 1b)	Hydrological Services TB4 0.01" Tipping Bucket - used to measure rainwater levels (See Figure 2d)
Diffuse Horizontal Pyranometer (See Figure 1c)	** Data is sent to a Campbell Scientific CR1000 data logger.*
Precision Infrared Radiometer (See Figure 1d)	
Total Ultraviolet Radiometer (See Figure 1e)	

See Figures 1, and 2 in figures section for photos of instruments.

3.2 Rainwater Collection Demonstration System

In 2013, Charles Upshaw, a PhD student in mechanical engineering who studied integrated energy and water systems for residential structures became interested in learning more about rainwater harvesting systems first-hand, so he set out to build a smaller-scale system on the ETC rooftop as part of the SWEAT Lab. The motivation for building the system was to three-fold: 1) Experience the learning exercise of designing a rainwater collection system, 2) Create a small-scale system that could be used for rainwater-related research ideas, and 3) Provide a demonstration system to educate students and others on rainwater collection.

This project was funded by the university's Green Fee Grant, a tuition-funded program that funds sustainability research and demonstration projects on campus, with design and pre-construction work beginning in Fall of 2014. The catchment roof structure was completed in June 2015 after several delays due to unexpected structural design issues prompting a re-design, as well as bad weather. The rainwater system build-out was completed in the winter of 2015/2016, when undergraduate student Yuval Edrey assisted in assembling the rainwater collection tank and plumbing the collection conveyance (See Figure 3b).

The rainwater harvesting system (RWH), features a welded steel catchment structure (104 ft^2) for rain collection and a 330 gallon storage tank (See Figures 3 b-d). Rainwater is collected in the tank via a system of pipes. Water first passes through the leaf-eater filter (to screen out large debris), then flows into a first-flush diverter that catches and isolates the first round of dirty water and residue that have accumulated on top of the catchment structure (Seen in Figure 3c). Once the first flush diverter fills, a floating ball seals further water from entering, diverting clean water to the tank via a downspout pipe that enters a Tee where both the tank and a spigot with a hose are attached.

3.3 Rooftop Garden

With the rainwater collection system built out, there was a desire to build a garden to utilize the rainwater. Physics undergraduate student Heather Rose began working on the SWEAT Lab project in Summer 2016, focusing on building out a more extensive rooftop garden. Figure 4 shows the initial rooftop garden plans developed by Heather.
The garden features two steel troughs and three whiskey barrel planters, located in full sun for plants that require full sun. A large table with attached planters sits under the catchment roof structure to house plants that require full or part shade. Windscreens were built around the table, and

one of the troughs to protect plants that are susceptible to wind damage.

For structural safety, plant beds had to be placed in accordance with the support beams built into the roof. Water containment was also key to prevent any damage to the roof. Built into the rainwater harvesting system was an overflow drain that is directed into a plant bed supported by a steel beam if the cistern were to overflow. The cistern was also placed on top of a large wooden platform to prevent any unexpected leakage from soaking into the roof. Large rubber mats were placed beneath the cistern and all planters to ensure water would not be absorbed by the roof and would instead divert to the storm drains. (See Figure 5)

All structures on the roof had to be either heavy enough to withstand high wind speeds, or strapped down to the steel catchment roof. (See Figure 6)

Student researchers are maintaining and expanding the garden as part of self-directed research projects. In the garden, students experiment with growing different kinds of plants while learning first hand how to keep crops thriving and healthy for effective food production.

3.4 Solar-Powered Drip Irrigation System

Prior to the construction of the Solar-Powered Drip Irrigation System in Fall 2016, students hand watered rooftop garden plants using collected rainwater or a hose connected to the ETC building's potable water system. The Solar-Powered Drip Irrigation system was designed by undergraduate research assistants Yuval Edrey and Heather Rose, and installed in the Fall of 2016. To date, all rooftop garden plants are watered via the solar powered drip irrigation system.

The Solar Powered Drip Irrigation System features a 12V DC Seaflo Pressure Pump, a Seaflo Accumulator Tank, and Raindrip Automatic Timers all powered by a 12V DC Deep Cycle Battery being charged by a 100Watt Solar Panel. The system also features a Charge Controller, a Programmable Timer, a Digital Multimeter and a Power Inverter with two AC outlets and USB ports. All electronics are stored in a large plastic storage bench for protection from water exposure. (See Figures 7, 8 and 9)

The irrigation system is run by Raindrip Automatic Watering Kits. Three kits were purchased to allow for three watering zones, each containing their own soil moisture criteria. Each zone contains a timer for watering frequency and duration. For plant types that require more water, such as tomatoes, strawberries and other fruiting crop, a longer watering duration was set for this zone. For plants that require less water, such as kale, and other leafy greens, a shorter watering duration was set. All drip emitters have a flow rate of ½ gph (15 drip heads per zone) and are set to water once every 24 hours. (See Figure 10)

A clear PVC pipe was installed to view cistern water level, with a non-translucent removable sleeve to prevent algae growth. A water log was created to monitor how much water is in the cistern and how much water plants are consuming. When cistern water level is low due to insufficient rain, students fill up the cistern using the building's tap water connection, and take note of the water level in the cistern in the water log.

4. SWEAT Lab-Related Research and Student Project Learning Outcomes

4.1 Solar Radiation and Weather Data Collection Learning Outcomes

The original purpose of building the lab was to collect solar radiation data to calculate the optimal orientation and tilt for solar panels in Austin, TX. These data were compared to theoretical models and data from other locations in the US. The results challenged the rule of thumb that an orientation of due south was optimal for energy production and showed that, due to early morning haze, 10 degrees west of south was optimal. This work led to a peer-reviewed journal publication. [3]

Besides the usage of the data, having and maintaining the lab has given hands-on experience to multiple students or enabled graduate research. These students have learned that, in the real world, things break, computers fail, and results are not always neat and tidy. This set of lessons has sharpened some students' acumen while giving them broad decision power over maintaining and building the lab.

4.2 Rooftop Garden Learning Outcomes

Students experimented with growing different types of plants in the rooftop garden. Due to Austin's infamously unpredictable weather, several plants that normally thrive in Texas did not survive unanticipated prolonged periods of sub-freezing temperatures (specifically cacti and succulents). Plants that did surprisingly well were kale, spinach, strawberries, rosemary and lavender, despite temperature swings from 20^{o}F to 100^{o}F throughout the year. Tomatoes, shown in Figure 11, also proved to be great summer crops for the rooftop garden.

4.3 Solar-Powered Drip Irrigation System Learning Outcomes

Another challenge that unusually low temperatures brought was pipe freezing. During the week in January of 2017 when temperatures were below freezing for over a week, one of the pipes to the cistern, froze and cracked, causing the cistern to leak.

4.4 Student Project: ReGrow Project

The ReGrow project, another Green Fee project run by undergraduate student Heather Rose, had its initial rooting trials in the rooftop garden. For this project, students took pieces of food scrap (specifically lettuce, broccoli, leeks, and onions) and planted them in the garden. Some of the scrap pieces grew into new plants. Students saw the most success from growing new roots when food scraps were soaked in water. With this, it was decided to continue the experiment hydroponically with lettuce plants in the Welch Greenhouse (for a more controlled environment). Despite extra care and consideration in system design, the students still encountered system leaks and algae growth in the grow tubs. (See Figure 12)

4.5 Student Project: Cultivation of Little Bluestem Grass for Graduate Research

In collaboration with the UT Fire Research Group, little bluestem grass is being cultivated for graduate student Savannah Wessies in this group who is researching brush fires of little bluestem grass. Savannah was originally purchasing little bluestem grass for her research. Using designated planter beds in the rooftop garden, undergraduate student Heather Rose was able to grow these grasses for her to help conserve limited funds. Once this grass is fully-grown Savannah will harvest and combust it in the current Fire Research Lab, below the roof on the tenth floor to measure its combustion rate and products. [4] (See Figure 13)

4.6 Student Project: Solar Dryers, Projects with Under-served Communities Team Mexico 2018

Projects with Under-served Communities, or PUC, is a unique program at the University of Texas at Austin that combines the two challenges of community need and student enrichment in an innovative project-based, service-learning collaboration between the International Office, the Cockrell School of Engineering, and the School of Social Work. [5]

The PUC Mexico Team is collaborating with an NGO partner Tejiendo Alianzas to design and construct a solar drying station for the mesquite flour production in Santiago Suchilquitongo, Oaxaca. The current process for creating mesquite flour is costly, time-consuming and lends to high loss in crop. The mesquite flour production facility is a catalyst program that will fund other community initiatives and the livelihood of the families involved.

The team of students in the Department of Civil Engineering at UT Austin have designed and built solar dryers that are currently being tested in the SWEAT Lab. Students are testing the dryer's functionality by measuring internal temperature, humidity, airflow and heat retention after sunset. Data loggers and thermocouples are used to track temperature changes in the dryers throughout the day, and these values are being compared to the SWEAT Lab's ambient temperature and humidity data. The team will soon begin testing with mesquite pods to see how long the pods take to lose 10-12% of their water content, and if they will be deemed "usable" for mesquite flour production. (See Figure 14)

This project has presented unexpected design challenges to the students. Challenges such as high wind speeds damaged some of the solar dryers, calling for minor reconstruction and redesign. The team has also needed to extend their testing phase due to unusually long stretches of cloudy days. The SWEAT Lab weather data has greatly assisted with tracking ambient conditions, particularly with the ability to go back in time to view historical weather conditions.

Once the testing phase is complete, and any design changes that need to be made are implemented, the solar dryers will go with the team to Mexico to work with the community of Santiago Suchilquitongo to implement the solar dryers. The PUC Mexico team will be working with the community, Tejiendo Alianzas, and local university students to manufacture, and install their more effective drying system, allowing for more efficient flour production during season. Over the course of the project, they will work closely with community members to ensure the design meets community needs, and is also sustainable.

4.7 Student Project: Spring-based Solar Tracker

Aligning a solar panel so that it tracks the sun's position in the sky throughout the day is one of the most effective ways to increase power generation. Today's systems use sensors, motors, and processors to align solar panels with the sun throughout the day. While these devices are known to increase power generation, they are complex, expensive, and ultimately drive up the cost of solar energy.

Engineering students Mandeep Patel, Taylor Zhou and Michael Liu are developing a passive spring-based solar tracking system that reduces costs by removing many of the parts required. Their unique solar tracker uses springs made of a special material that contract with the sun's heat and tilt a solar panel to face the sun directly throughout the day. The team expects their device will greatly increase the efficiency of solar panels while eliminating the complexity and additional costs of a sensor-motor based system.

The team will be testing their device in the SWEAT Lab in the summer of 2018. The plan is to attach a solar panel to their tracking device and measure the power generated over the course of the day. At the same time, they will setup a duplicate solar panel in a stationary position, also measuring power generated throughout the day. The team will use these data to calculate the increased efficiency in power generation their device creates and then compare this efficiency to the current industry standard for solar tracking technology.

These student projects all presented unanticipated challenges, as is always the case with real-world application of engineering. Challenges such as unanticipated temperature fluctuations, system leaks, high wind speeds and complexities brought on by bioforms all served as excellent learning experiences to the students with relatively low risk.

5. Conclusions and Future Work

The University of Texas at Austin has a long history of hands-on solar, energy, water, and food research on the roof of the mechanical engineering building. The latest incarnation, the SWEAT Lab, has been a student-driven effort to establish and build out the various systems. Research and student learning in the Webber Energy Group and with other research groups on campus have been positively impacted by the SWEAT lab, and will continue to be so moving forward.

The Webber Energy Group plans to add a hydroponics system to the rooftop garden. This will be a space where students can learn about hydroponic growing systems and where they can experiment with designs to optimize water and energy efficiency. The group also plans to work with other research groups across campus to dedicate part of the space to research in areas of biology, horticultural and agriculture.

Acknowledgements

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In addition to research work on topics generally related to energy systems at the University of Texas at Austin, Charles Upshaw, Joshua Rhodes, and Michael Webber are equity partners in IdeaSmiths LLC, which consults on topics in the same areas of interest. The terms of this arrangement have been reviewed and approved by the University of Texas at Austin in accordance with its policy on objectivity in research.

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[1] SWEAT Lab website
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[2] Texas Advanced Computing Center (TACC)
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[3] Rhodes, J. (2014). A multi-objective assessment of the effect of solar PV array orientation and tilt on energy production and system economics. Solar Energy 108(2014) 28-40

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[5] Projects with Underserved Communities, Oaxaca Mexico 2017-2018 website
<https://pucmexico2018.wixsite.com/oaxaca>
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Figures 1 through 6

Figure 1: Eppley Lab Solar Tracking Equipment
a.) Direct Pyrheliometer
b.) Global Horizontal Pyranometer
c.) Diffuse Horizontal Pyranometer
d.) Precision Infrared Radiometer
e.) Total Ultraviolet Radiometer

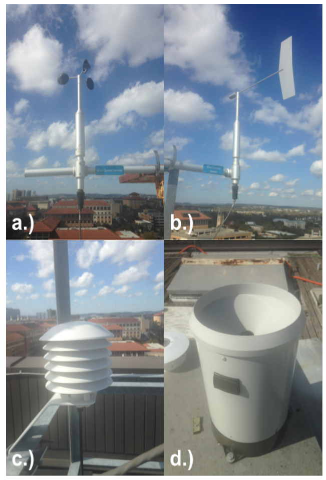

Figure 2: Weather Data Equipment
a.) Met One 010C Wind Speed Sensor
b.) Met One 020C Wind Direction Sensor
c.) Vaisala HMP60 Temperature and Humidity Sensor
d.) Hydrological Services TB4 0.01" Tipping Bucket

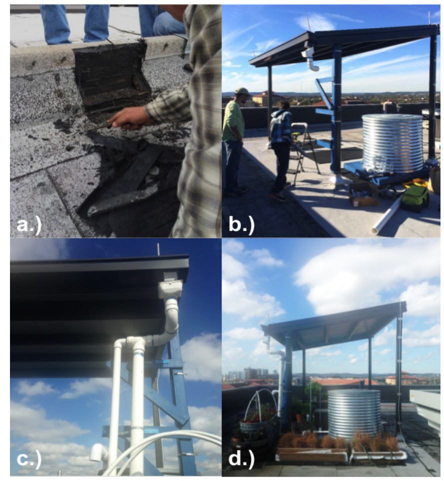

Figure 3:
a.) Unforeseen structural conditions on the ETC roof required a structural re-design for RWH system
b.) Several students supported the design and construction of the RWH system
c.) Leaf-Eater Filter and First flush diverter with overflow drain
d.) Steel welded "mini roof" and 330 gallon cistern

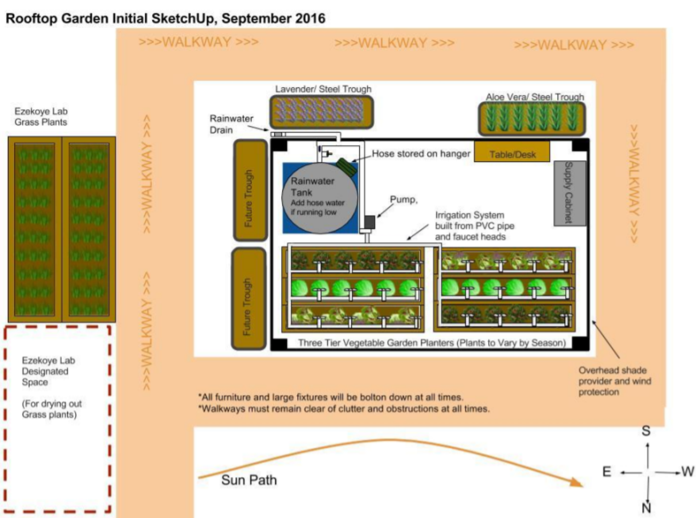

Figure 4: Initial sketch-up of rooftop garden.

Figure 5: Rainwater collection system pipe configuration with leaf-eater filter, first flush diverter, water level indicator and overflow drain.

Figure 6: Table is strapped to catchment roof structure using ratchet straps. Windshield was built around wind sensitive plants.

Figures 7 through 14

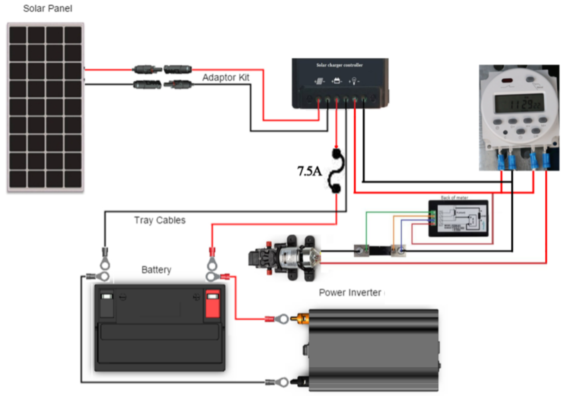

Figure 7: Wiring Diagram for Solar Powered Pump

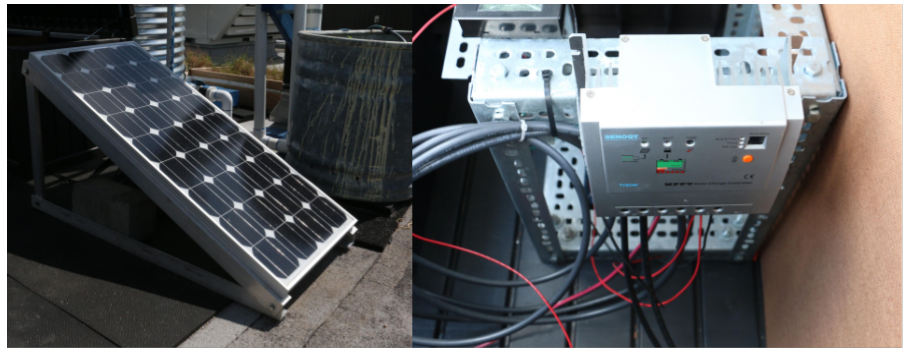

Figure 8: Renogy 100W 12V Monocrystalline Solar Starter with 20A MPPT Charge Controller

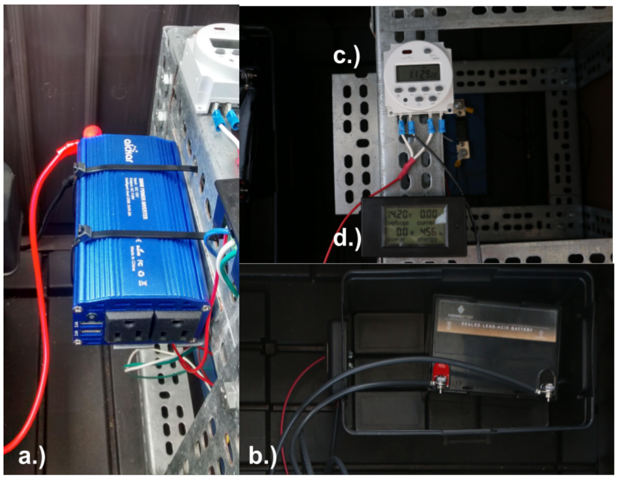

Figure 9:
a.) Aickar 300W Car Power **Inverter**, DC 12V to AC 110V
b.) 12V DC Deep Cycle Battery
c.) Programmable Timer, Time Switch Relay
d.) Digital Multimeter, voltage shown is battery voltage.

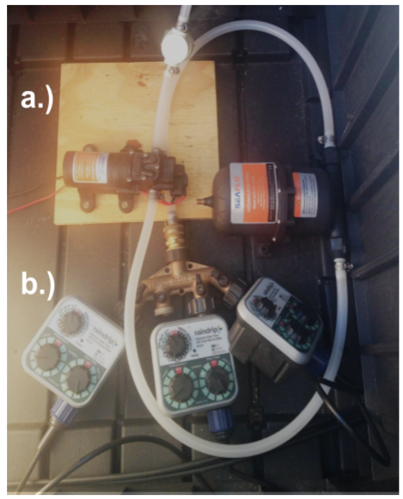

Figure 10:
a.)Seaflo 12V Pump with Seaflo Accumulator Tank.
b.)Three Raindrip Automatic Timers for watering frequency and duration.

Figure 11: Big plump tomatoes grown right on the roof of ETC!

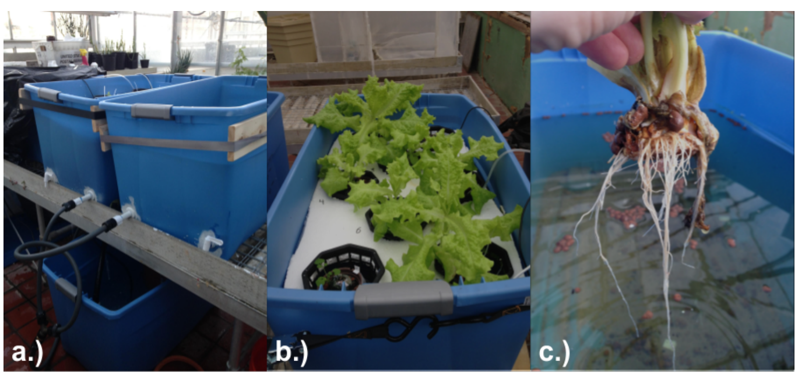

Figure 12: ReGrow Project
a.) Recirculating raft hydroponic system, housed in Welch Greenhouse
b.) Lettuce grown from seed in raft hydroponic system
c.) Water roots from lettuce regrown from food scrap

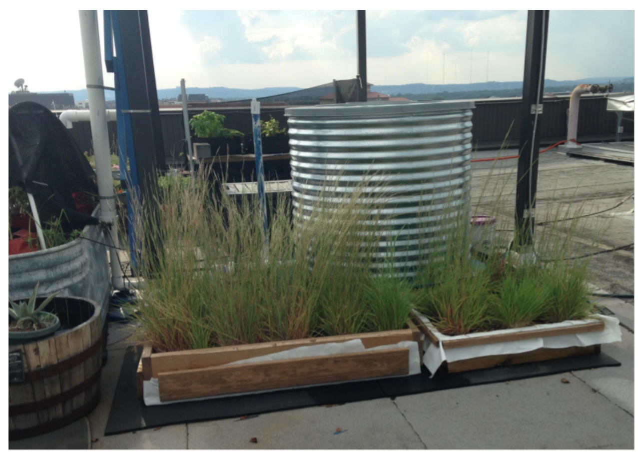

Figure 13: Little Bluestem grass being grown for UT Fire Research Group

Figure 14: Solar Dryer designed and built by Team Mexico 2018 for Projects with Under-served communities